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THE APPLICATION OF DRYING-RATE NOMOGRAPHS TO THE ESTIMATION OF TUNNEL-DEHYDRATOR DRYING CAPACITY. I. RICED WHITE POTATOES

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Both designers and operators of vegetable dehydrators have need for information about the rates at which different vegetables will dry under the range of conditions likely to be encountered in commercial dehydrators. The designer must have an estimate of drying time in order to determine the dimensions, the air flow, and the heat supply required for a drier of a given capacity. The operator needs a rational basis for the determination of optimum tray-loading density and the proper degree of recirculation of air, both of which are inseparably related to drying time. If an existing dehydrator is to be used for some new product, an estimate of the drying time of the new product must be made before accessory preparation and packaging equipment can be properly designed to match in capacity.

The time required to dry prepared pieces of a vegetable in a hot-air dehydrator is known to depend upon at least the following factors: variety of vegetable, method of preparation, shape and size of piece, thickness of layer, type of tray or other support, mode of exposure to the air stream, the temperature, humidity, and velocity of the air stream, and the type of drying cycle which is used. That is, the drying time depends upon both the characteristics of the dehydrator and the properties of the vegetable itself.

The characteristics of a dehydrator may usually be described with reasonable accuracy on the basis of the thermodynamic properties of air and water vapor and the principles that govern the flow of air. The pertinent properties of vegetables, on the other hand, can be determined only by experiment.

This series of circulars, identified by the coding AIC-31, presents experimental data on the drying times of important vegetables, correlated and summarized in the form of nomographs in order to facilitate their practical use. This, a revision of the first circular in the series, outlines the general method of using drying-time nomographs and presents nomographs for the tray-drying of riced white potatoes. An example is included.

Physical Relations in a Tunnel Dehydrator*

The application of heat and material balances to simple parallel-flow or counterflow tunnel dehydrators leads to the following important equations:**

$$\Delta\, t_d = \pm\, b\, \Delta\, T \tag{1}$$

$$b = \frac{83\, M\, L_o}{G\, \theta_h\, (T_o - 1)} \tag{2}$$

$$F = \frac{0.012\, M\, L_o}{\theta_h} \tag{3}$$

$$r = \frac{a' - a_m}{a'' - a_m} \tag{4}$$

$$B = 1250 \left[r - \frac{(1 - r)(t'_d - t_m)}{(t'_d - t''_d)} \right] \tag{5}$$

$$D = 15\, G\, [(1 - r)(t'_d - t_m) - r(t'_d - t''_d)] \tag{6}$$

In addition, the wet-bulb temperature of air circulating through any section of a vegetable dehydration tunnel in which no reheating takes place remains substantially constant.

The nomenclature is as follows:

a - absolute humidity of air, consistent units
b - proportionality constant (see equation 2)
B - BTU supplied to dehydrator per pound of water evaporated
D - heat demand, BTU per hour
Δ - increment of, or change in, a variable
f - mathematical symbol meaning "function of"
F - input capacity, tons of prepared material per 24 hours
G - mass air flow through dehydrator, pounds of air per minute
L - tray loading density, pounds per square foot
M - total useful tray surface in dehydrator, square feet
r - fraction of air which is recirculated

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*For a more complete exposition of the principles of drying, see U. S. Department of Agriculture Miscellaneous Publication No. 540, "Vegetable and Fruit Dehydration", June, 1944.
**Equations (1), (4), (5), and (6) are not exact, but computations based upon them will be sufficiently precise for the practical design and operation of vegetable dehydrators.

t - air temperature, °F.
T - moisture content, ratio of total water to dry solids
V - air velocity, linear feet per minute, in free space above loaded tray
θ - drying time, hours

Superscripts: ' refers to air inlet conditions
" refers to air exhaust conditions

Subscripts: d - dry-bulb temperature
f - final or product conditions
h - dehydrator conditions, i.e. holding or retention in dehydrator
m - outside or make-up air conditions
o - initial or input material conditions
r - reference conditions where $f(V, L_o)$ or $f(\theta_1) = 1$
w - wet-bulb temperature
1 - drying time in high moisture range (above T = 0.1 for riced potatoes)
2 - drying time in low moisture range (below T = 0.1 for riced potatoes)

These general equations are made specific by insertion of conditions imposed by the design of the dehydrator, by specifications which must be met, and by the material to be dried. Corresponding limits for the integration of equation (1), the total tray surface, and the air flow are fixed by the design of the dehydrator. The final moisture content of the material, and sometimes the finishing temperature and maximum tray loading density, are included in the specifications for the product. The initial moisture content is characteristic of the material to be dried.

Equation (1), in which the positive sign (+) pertains to a parallel-flow tunnel and the minus sign (-) to a counterflow tunnel, may be integrated by substituting suitable pairs of limits. For parallel-flow, the pairs are T_o and t'_d, or T_f and t''_d; for counterflow, T_o and t''_d, or T_f and t'_d. Upon integration, equation (1) becomes;

For parallel-flow, $$t_d = t''_d + b(T - T_f) = t'_d - b(T_o - T) \qquad (7)$$

For counterflow, $$t_d = t''_d + b(T_o - T) = t'_d - b(T - T_f) \qquad (8)$$

Stated in words, equations (7) and (8) say that a straight-line relationship exists between the change in air temperature in the tunnel and the change in moisture content of the moist material.

Drying Characteristics of Vegetables

The drying-rate characteristics of certain vegetables are being established by this Laboratory. The following drying time nomographs pertaining to

riced white potatoes are presented in this circular:*

Figure 1 - Drying times from T_0 = 3.0 to T = 0.10 at reference conditions of L_0 and V.
Figure 2 - Effect of L_0 and V on data of Figure 1.
Figure 3 - Drying times from T = 0.10 to T_f.
Figure 4 - Effect of previous drying conditions on data of Figure 3.
Figure 5 - θ corrections for $T_0 > 3.0$.

The effects of tray-loading density and air velocity upon drying times from T_0 to T are related by the equation

$$\theta_1 \text{ (at } L_0, V) = \theta_{r_1} \cdot f(V, L_0) \tag{9}$$

In this equation, θ_{r_1} is the drying time from T_0 to T under reference conditions (L_0 = 1.2 lbs./sq. ft. and V = 850 ft./minute, cross air flow) as obtained from Figure 1, and values of $f(V, L_0)$ are obtained from Figure 2. The function, $f(V, L_0)$, must correspond to the values of L_0 and V under consideration and must be selected at the value of T to which θ_1 and θ_{r_1} apply. Below T = 0.10, drying times are substantially independent of air velocity and of tray-loading density, but are somewhat influenced by the rate at which the previous drying has taken place. This influence is expressed by the equation

$$\theta_2 = \theta_{r_2} \cdot f(\theta_1) \tag{10}$$

in which θ_{r_2} is a reference drying time obtained from Figure 3, and $f(\theta_1)$ is obtained from Figure 4. The function, $f(\theta_1)$, includes the effects of L_0, V, t_d, and t_w upon the drying time from T_0 to T = 0.10 and consequently includes indirect effects of these variables upon drying times below T = 0.10.

Use of Equations and Figures

The continuous operation of a tunnel dehydrator requires a balance between the demands made by the physical characteristics of the dehydrator and by

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*The material used for the drying experiments reported in this circular was white potatoes of the Oregon Russet variety. The potatoes were peeled in a mechanical abrasive peeler, trimmed and quartered by hand, washed, and steam-cooked at atmospheric pressure for 20 minutes. The cooked material was riced immediately (before cooling) in a hand ricer which formed shreds 1/8" in diameter. (If the potatoes cool appreciably, higher pressures are required for ricing, and a relatively dense, slow-drying string or shred is obtained.) The shreds fell directly from the ricer to the drying tray, and were not disturbed after falling into place. An open structure of loosely-piled, fast-drying strings was thus obtained for the drying experiments.

the drying-rate characteristics of the material to be dried. A range of conditions must be calculated to satisfy the demands of the dehydrator and of the vegetable separately; a combination of the two ranges establishes the possible operating condition. The process is illustrated in the following paragraphs.

Calculation of Drying Time (Material Characteristics)

Although the dry-bulb temperature conditions vary from point to point within a tunnel dehydrator, the drying-time nomographs, which are based upon constant temperature conditions, may be applied by means of a series of approximations. The replacement of the variables T and t_d by their terminal values in equations (7) and (8) leads to

$$t'_d - t''_d = \pm b\,(T_o - T_f) \qquad (11)$$

Equation (1) states that changes in T are directly proportional to changes in t_d. Consequently, a plot of T vs. t_d for a tunnel dehydrator is a straight line whose slope is +b for parallel-flow or -b for counterflow. The ends of the straight line are located by T_o, T_f, t'_d and t''_d. The solid line of Figure 6 illustrates this point for a counterflow tunnel, T_o = 3.0, T_f = 0.05, t'_d = 150°, and t''_d = 110°. An approximation to the straight line is shown by the dotted line which follows a series of steps. (The steps are laid out as shown, and satisfactory estimates of drying time may be obtained by using 5° temperature steps throughout. Where the drying is relatively rapid, 10° temperature steps will lead to little error. An arithmetic mean of the terminal temperatures of each step is entirely satisfactory with regard to accuracy. Over the moisture content range involving Figure 3 (T = 0.10 to T_f), a single temperature may be selected for the entire step, and the terminal or finishing temperature of the step may be used without appreciable error.) Each full step represents a portion of the drying process as though it were occurring at a constant temperature, and wet-bulb temperature remains substantially constant throughout the tunnel; the drying time nomographs may therefore be applied. For convenience in use of the nomographs, steps in T may be calculated from equation (7) or (8) so that the mean dry-bulb temperature for most of the steps will occur at even 5° points, thus minimizing interpolation within the temperature network. Numerical calculation of the steps will frequently be simpler than the graphical construction shown in Figure 6.

Table 1 details the steps of Figure 6 and the process of evaluating the drying time of riced white potatoes under the temperature and moisture conditions specified, and at a tray loading density of 1.5 lbs./sq. ft. and an air velocity of 700 ft./minute. In table 1, the step numbers correspond to those of Figure 6, t_d to the terminal air temperatures of each step, t_d av. to the arithmetic mean temperature prevailing during the step, t_d-t_w to the mean wet-bulb depression prevailing during the step (for an assumed constant wet-bulb temperature of 90° F.), $\Delta\theta_{r_1}$ to

Table 1. Steps in the Nomographic Estimation of Drying Time

Range from T_o to T = 0.10 (Figures 1 and 2)

Step No.	T	t_d	t_d av.	t_d-t_w*	$\Delta\theta_{r_1}$	θ_{r_1}	$f(V,L_o)$	θ_1
	3.00	110.0				0.00	---	0.00
1			113.8	23.8	0.38			
	2.45	117.5				0.38	(1.59)**	(0.60)**
2			120.0	30.0	0.26			
	2.08	122.5				0.64	(1.58)	(1.01)
3			125.0	35.0	0.24			
	1.71	127.5				0.88	(1.58)	(1.39)
4			130.0	40.0	0.24			
	1.34	132.5				1.12	(1.57)	(1.76)
5			135.0	45.0	0.25			
	0.97	137.5				1.37	(1.56)	(2.14)
6			140.0	50.0	0.30			
	0.60	142.5				1.67	(1.54)	(2.57)
7			145.0	55.0	0.46			
	0.24	147.5				2.13	(1.50)	(3.20)
8			148.4	58.4	0.47			
	0.10	149.3				2.60	1.47	3.82

Range from T = 0.10 to T_f (Figures 3 and 4)

Step No.	T	t_d	t_d av.	t_d-t_w	$\Delta\theta_{r_2}$	θ_{r_2}	$f(\theta_1)$	θ_2
	0.10	149.3				0.00	---	0.00
9			149.6	59.6	1.30			
	0.05	150.0				1.30	1.63	2.12

Total Drying Time = $\theta_1 + \theta_2$ = 3.82 + 2.12 = 5.94 hours.

*In non-reheating vegetable dehydrators, the wet-bulb temperature remains substantially constant. t_w is taken as 90° F. in this example. Other values may be appropriate, depending upon local atmospheric conditions, the amount of air recirculated, and other factors. A humidity chart is of importance in selecting a reasonable value.

**The values in parentheses are not required except for the investigation of conditions within the tunnel.

time increments for each step as evaluated from Figure 1, and θ_{r_1} to the sum of the increments for each step. The column of values of θ_{r_1} represents a reference drying time from which drying times may be calculated for any tray-loading density and air velocity, all under the specified terminal conditions of temperature and moisture content. In Table 1, the reference drying time is corrected by means of equation (9) and Figure 2 to the conditions of tray-loading density and air velocity specified. The data of the last column, θ_1 are the drying times corresponding to the values of T at the left under the exact conditions specified in the problem, for the range of T_o to T = 0.10. The evaluation of drying times below T = 0.10 is similar except that the reference drying time, θ_{r_2} is corrected by $f(\theta_1)$ only, according to equation (10) and Figure 4. The total drying time is the sum of θ_1 and θ_2. To illustrate the manner of evaluating the drying time increments, Step No. 7, occurring between T = 0.60 and 0.24, will be used. In Figure 1, lines drawn from the point (in the temperature network) representing $t_d - t_w = 55°$ and $t_w = 90°$ to the T axis at T = 0.60 and 0.24 intersect the θ_{r_1} axis at 0.97 and 1.44 hours, respectively. The difference in θ_{r_1} or 0.47 hour, is the time required for Step No. 7 to occur under reference conditions. The rest of the steps are evaluated similarly, and summed to obtain the total drying time under reference conditions.

In the illustration given, a value of t''_d was assumed and the corresponding value of θ_f was determined.* The evaluation of the counterflow tunnel requires that a range of corresponding values of θ_f and t''_d be established which will satisfy the demands imposed by the material. This range is obtained by assuming values of t''_d and determining the corresponding values of θ_f by the method illustrated.

Calculation of Retention Time (Dehydrator Characteristics)

The demands imposed by the dehydrator may be calculated easily by combining equations (2) and (11) to obtain the following expression for retention time:

$$\theta_h = \frac{83\ M\ L_o\ (T_o - T_f)}{G\ (t'_d - t''_d)(T_o - 1)} \tag{12}$$

The substitution of assumed values of t''_d in this equation permits the calculation of corresponding values of θ_h, thus establishing a set of values that will satisfy the characteristics of the dehydrator.

*The unknown variables, depending upon the problem, may be any two of the following: T_f, t'_d, t''_d, or θ_f. Two of these can be specified under normal conditions. The relationship between the remaining two variables can be determined by a process similar to that described in the text.

Determination of Operating Conditions

The particular values of the variables that will satisfy the necessary operating conditions are obtained by plotting a curve of drying time (θ_f) vs. t''_d (material characteristics) and a curve of retention time (θ_h) vs. t''_d (dehydrator characteristics) on the same coordinates of θ vs. t''_d. Calculation of three points on each curve is generally enough to establish their point of intersection with sufficient accuracy. The intersection indicates the only possible values of θ and t''_d under which the dehydrator will operate and still satisfy all the conditions previously imposed.

With the information thus obtained, equations (3), (4), (5), and (6) may be used to estimate the capacity, amount of air recirculated, heat consumption, and heat demand of the dehydrator. The errors in calculations of the type described are considered to be less than the uncertainties which arise from uneven distribution of air flow, and irregularities in operation and charging of the dehydrator.

General Notes

Certain limitations of the procedure described in this circular must be noted. Actual conditions within a commercial dehydrator are more complex than the idealized situation that is described above. The air distribution in commercial tunnels is rarely uniform, air temperatures fluctuate, and trays are never loaded quite uniformly with the prepared vegetable. Most types of tunnel are substantially out of action during the time end doors are open for the movement of trucks. Such factors should be recognized, and their effects discounted insofar as possible.

Variations in air velocity of $\pm$ 100 ft./min. across a tray do not appreciably affect drying rates in the normal velocity ranges (800 to 1100 ft./min.). However, a good average velocity should be used for calculations, and the total mass flow of air should be known as accurately as possible. Moderate variations from uniform tray loading cause only a slight decrease in tunnel capacity. Down-time for truck movement may be established with accuracy.

The methods of measuring some of the variables considered in this circular influence the application of the data. Specifically involved are the methods of determining moisture content in the dry product, air velocity, and air temperature.

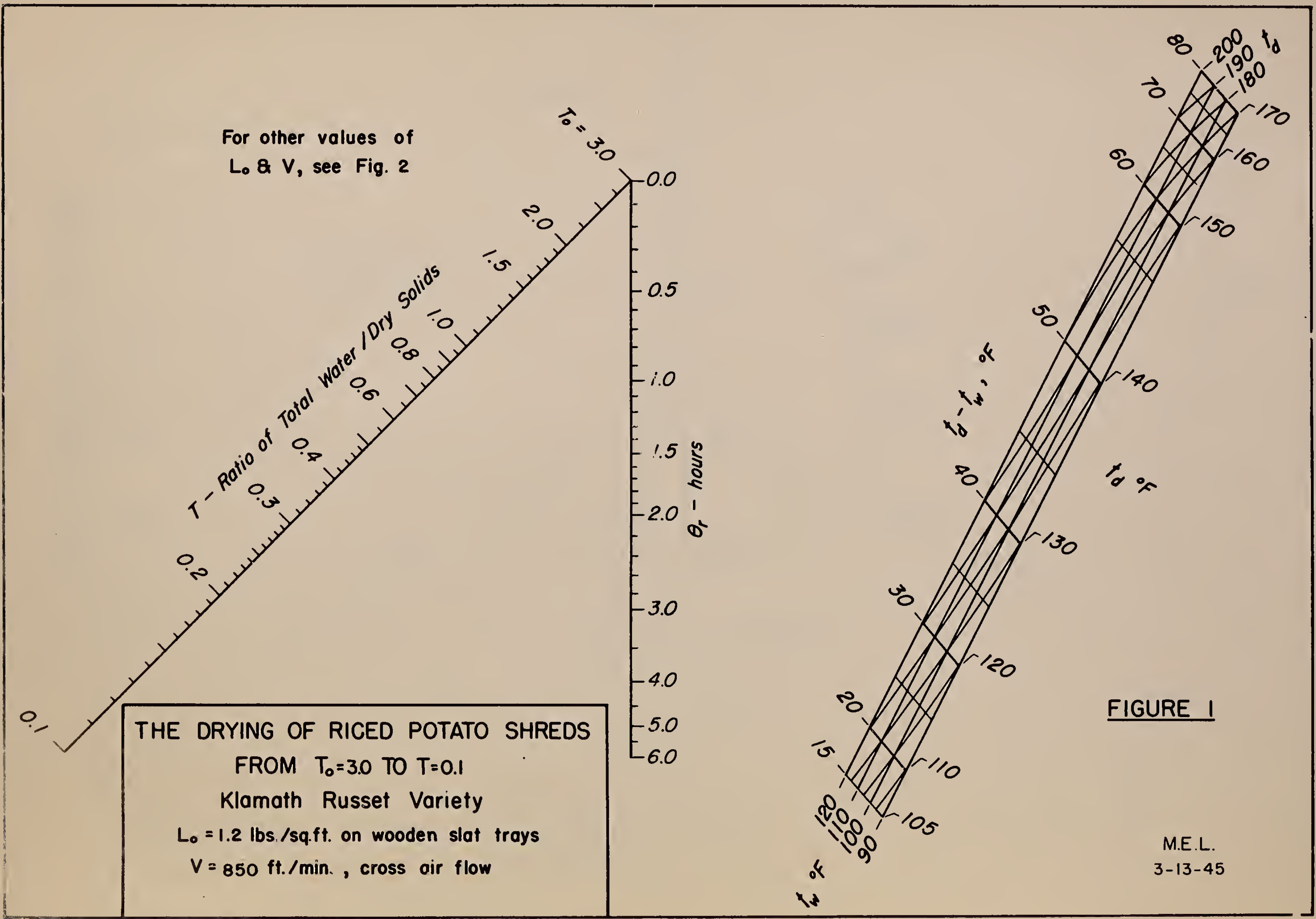
The moisture content of the dry material was determined as follows: After at least 24 hours of equalization in a sealed container, the entire sample was ground in a Wiley mill to pass a 2 mm. screen, and the product was thoroughly mixed. Portions of the ground material were dried for 16 hours at 70° C. and an absolute pressure of 8 to 10 mm. of mercury. The loss in weight was taken as representing moisture loss. The method gives somewhat higher results than the 6-hour method which has commonly been used in inspection of dehydrated vegetables for Government purchase. The difference between results by the two methods is somewhat variable,

but is probably less than 1% for riced potatoes in the range of 6 to 8 percent moisture.

During the experimental work, the air velocity was measured by a Biram-type anemometer resting on an empty tray in the drier. The results reported represent an average of readings taken at several points along the mid-line of the tray, perpendicular to the direction of air flow. The air velocity so measured was calculated to the equivalent free space velocity above the loaded trays for preparing Figure 2, the $f(V, L_0)$ nomograph. The average thickness of material on the tray was taken as 0.46" for L_0 = 1.2 lbs./sq. ft., and the thickness was assumed to be directly proportional to the tray loading density.

The values of air temperature used in the drying time nomographs were measured at the leading edge of an experimental tray which was 2 feet wide, measured in the direction of air flow. The drying rates observed were therefore somewhat lower than would have occurred on a tray so narrow that no appreciable fall in air temperature took place. Total drying times to T_f = 0.1 would, however, have been only slightly affected.

If the change in conditions across a tray be required, as is the case in designing cabinet dehydrators, approximate solutions may be obtained by combining instantaneous heat and material balances with drying rates obtained from the nomographs, and repeating for a series of time intervals in each of which the drying rate may be assumed to remain constant. No general analytical solution is known for the unsteady state conditions characteristic of batch driers, of which cabinets are an example.



THE DRYING OF RICED POTATO SHREDS
FROM T_o=3.0 TO T=0.1
Klamath Russet Variety
L_o = 1.2 lbs./sq.ft. on wooden slat trays
V = 850 ft./min., cross air flow

FIGURE I

M.E.L.
3-13-45

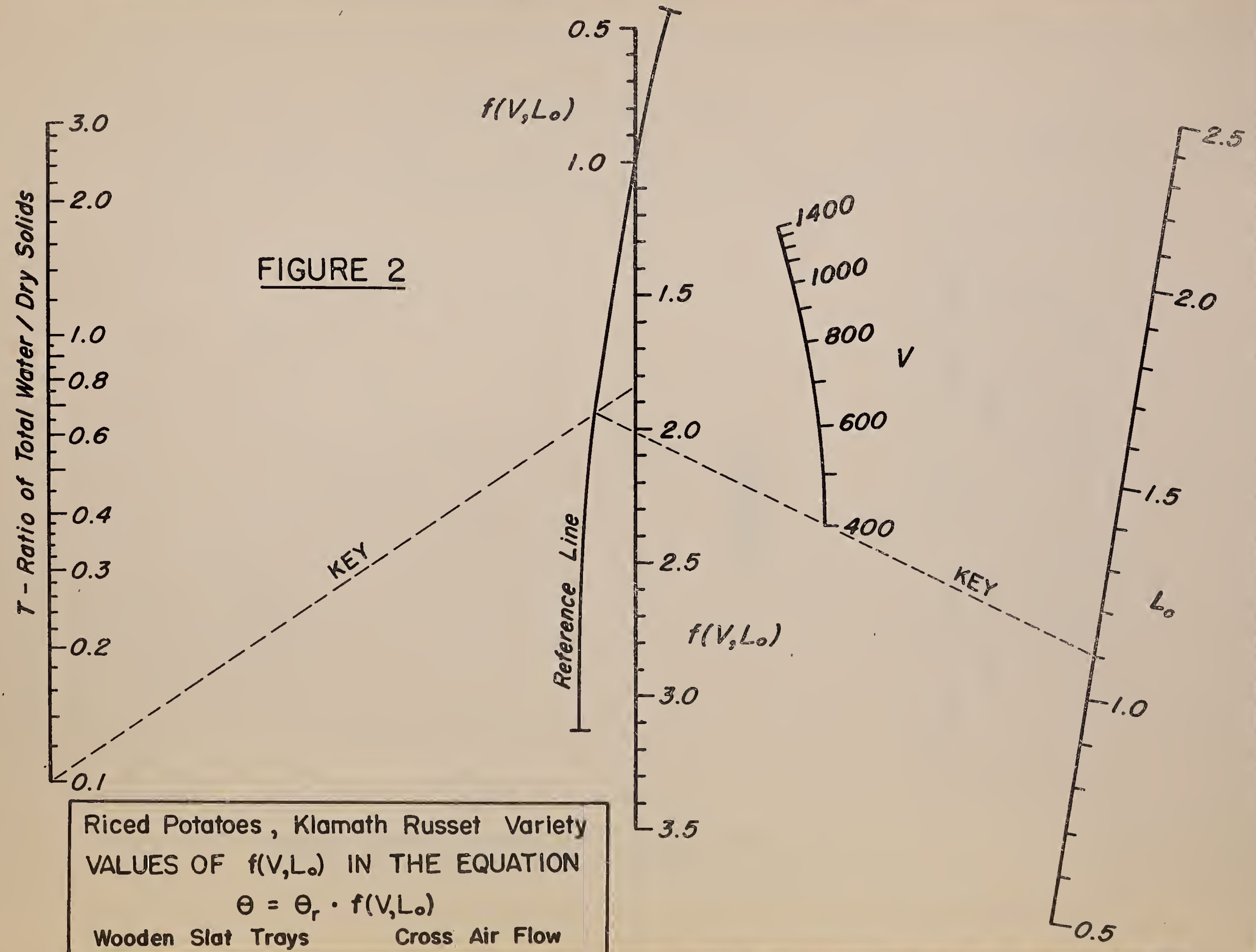


FIGURE 2

Riced Potatoes, Klamath Russet Variety
VALUES OF $f(V,L_o)$ IN THE EQUATION
$$\theta = \theta_r \cdot f(V,L_o)$$
Wooden Slat Trays Cross Air Flow

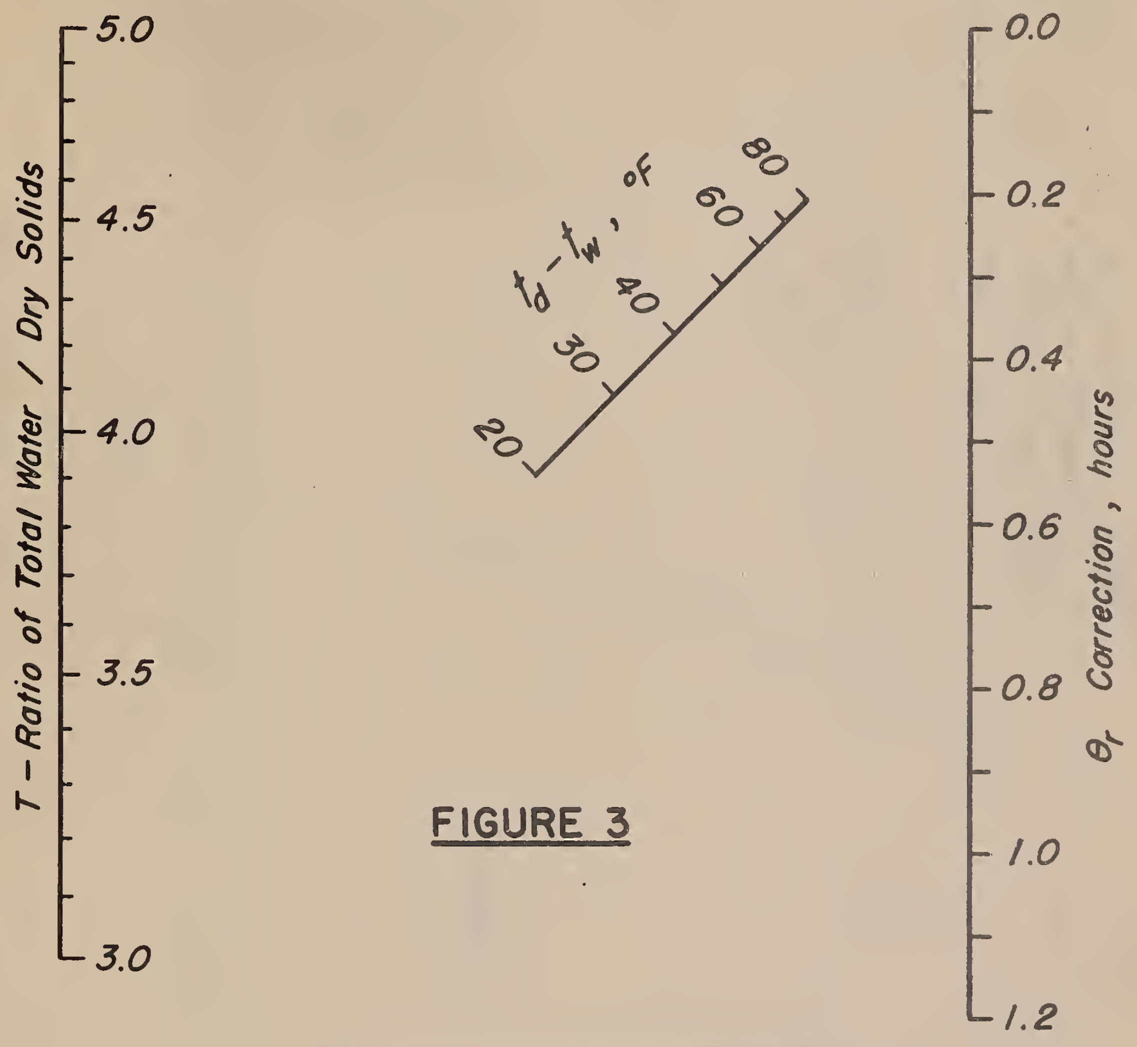


FIGURE 3

Riced Potatoes, Klamath Russet Variety

CORRECTION OF θ_r FOR $T > 3.0$

$L_o = 1.2$ lbs./sq.ft. on wooden slat trays

$V = 850$ ft./min., cross air flow

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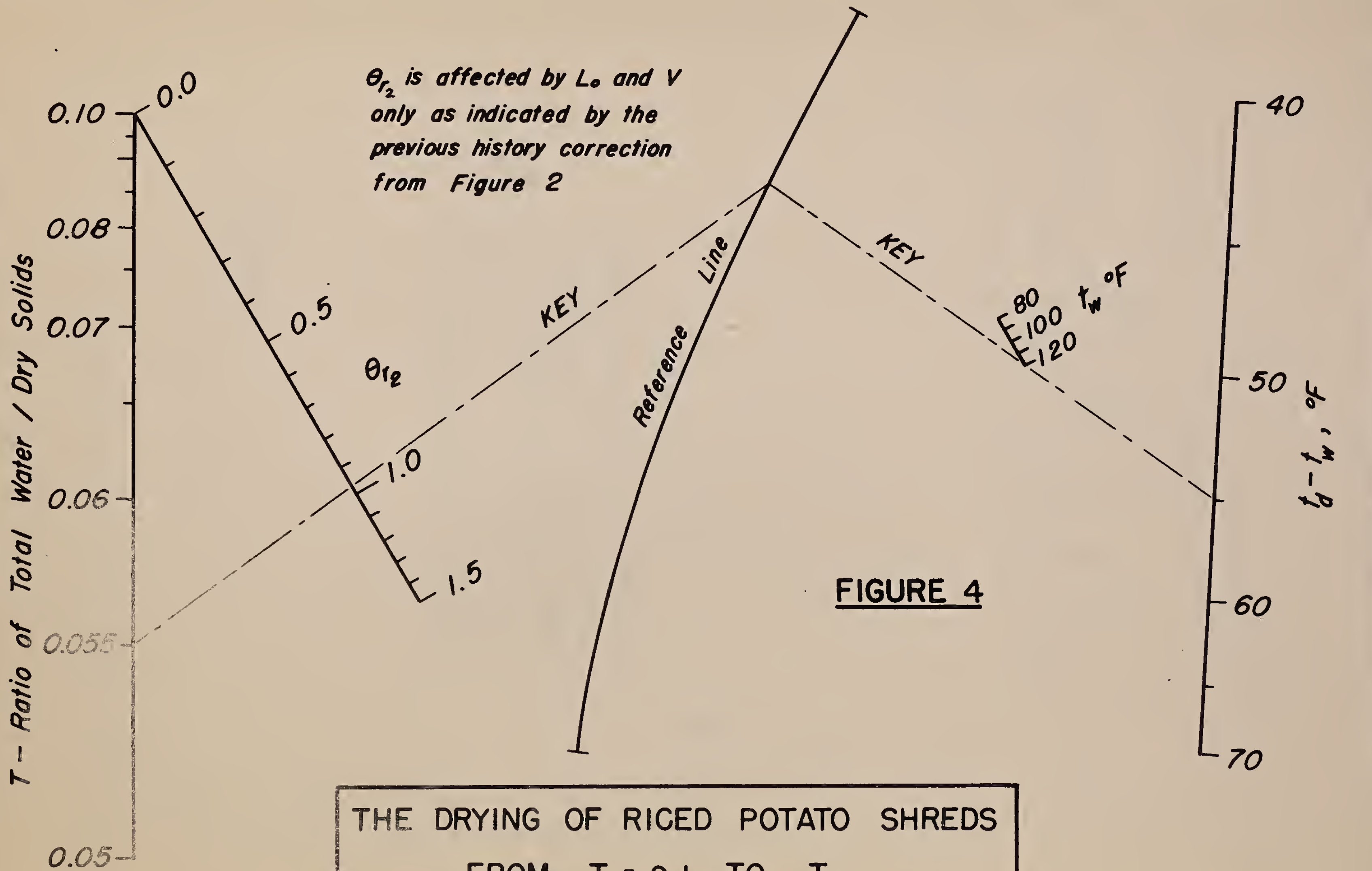

FIGURE 4

THE DRYING OF RICED POTATO SHREDS
FROM T = 0.1 TO T_f
Klamath Russet Variety
Wooden Slat Trays Cross Air Flow

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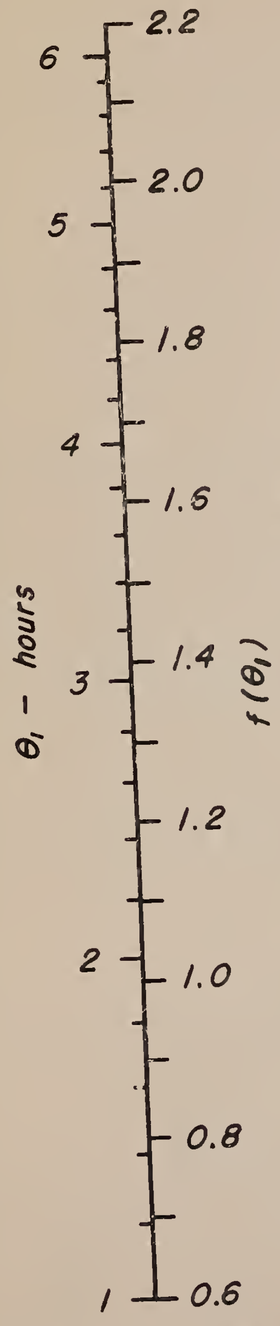
FIGURE 5



Procedure for Determination of θ_2:

1. Find θ_1 from Figs. 1 & 2 (Rept. No. ED-6-12-5)
2. Obtain $f(\theta_1)$ corresponding to θ_1 at left.
3. Find θ_{r_2} from Fig. 1 (this report)
4. Determine θ_2 using the equation:

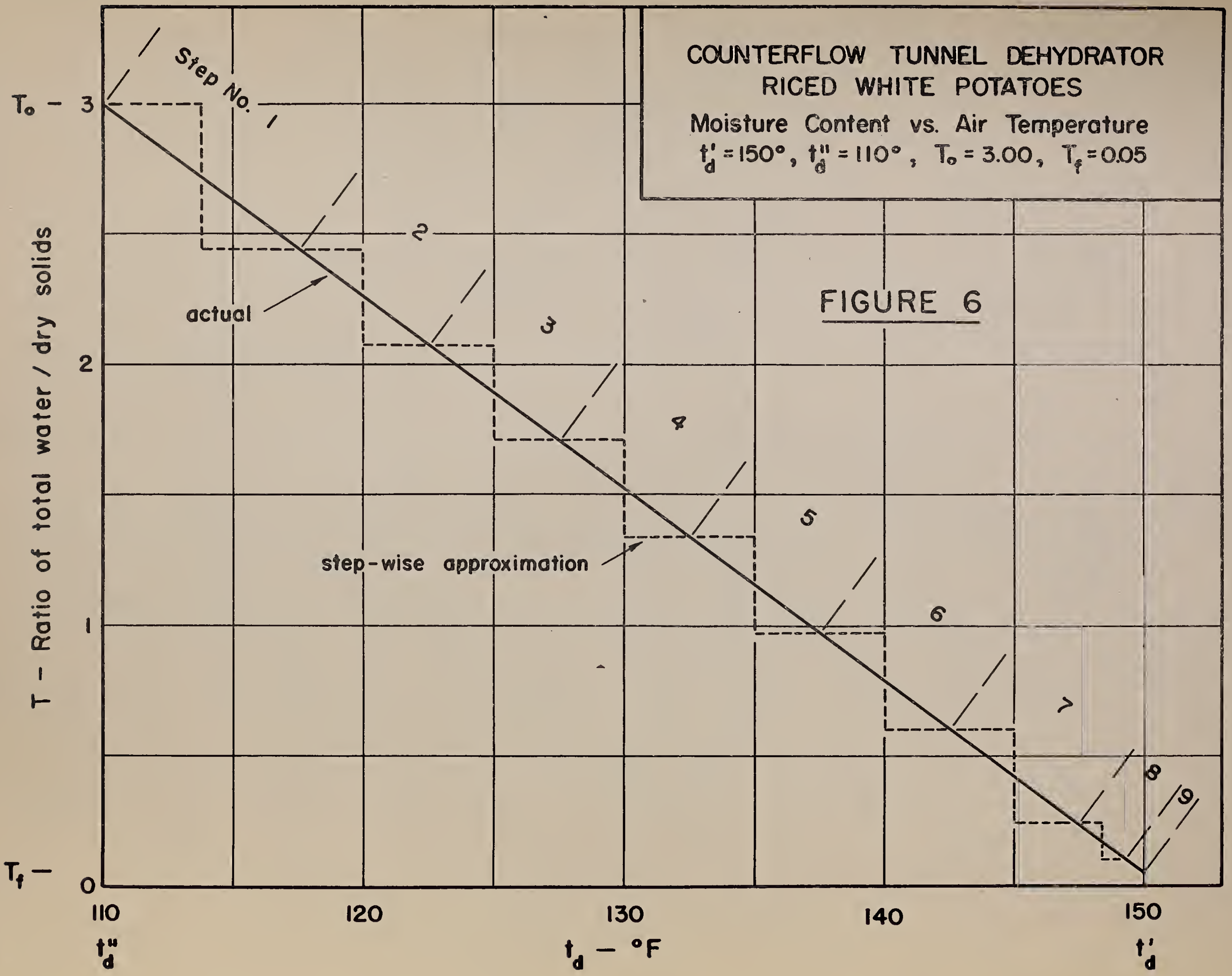
$$\theta_2 = \theta_{r_2} \cdot f(\theta_1)$$

M.E.L.
3-13-45

Riced Potatoes, Klamath Russet Variety
VALUES OF $f(\theta_1)$ IN THE EQUATION

$$\theta_2 = \theta_{r_2} \cdot f(\theta_1)$$

Wooden Slat Trays — Cross Air Flow


COUNTERFLOW TUNNEL DEHYDRATOR
RICED WHITE POTATOES
Moisture Content vs. Air Temperature
$t_d' = 150°$, $t_d'' = 110°$, $T_o = 3.00$, $T_f = 0.05$
FIGURE 6
T - Ratio of total water / dry solids
T_o - 3
2
1
T_f - 0
110
120
130
140
150
t_d''
t_d — °F
t_d'
Step No. 1
2
3
4
5
6
7
8
9
actual
step-wise approximation